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Research article

Modeling the carbon-energy-water nexus in a rapidly urbanizing catchment: A general equilibrium assessment

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ABSTRACT

Energy and water systems are interdependent and have complex dynamic interactions with the socio-economic system and climate change. Few tools exist to aid decision-making regarding the management of water and energy resources at a watershed level. In this study, a Computable General Equilibrium (CGE) model and System Dynamics and Water Environmental Model (SyDWEM) were integrated (CGE-SyDWEM) to predict future energy use, CO_2 emissions, economic growth, water resource stress, and water quality change in a rapidly urbanizing catchment in China. The effects of both the CO_2 mitigation strategies and water engineering measures were evaluated. CO_2 mitigation strategies have the potential to reduce 46% CO_2 emissions and 41% energy use in 2025 compared with reference scenario. CO_2 mitigation strategies are also found to be effective in promoting industrial structure adjustment by decreasing the output of energy- and water-intensive industries. Accordingly, it can alleviate local water stress and improve water environment, including a 4.1% reduction in both domestic water use and pollutant emissions, a 16.8% water demand reduction in the labor-intensive industry sector, and 4.2% and 4.4% decrease in BOD_5 and NH_3-N loads in all industrial sectors, respectively. It is necessary to implement water engineering measures to further alleviate water resource stress and improve water quality. This study improves the understanding of the feedbacks of CO_2 abatement on water demand, pollutant discharges, and water quality improvement. The integrated model developed in this study can be used to aid energy, carbon, and water policy makers to understand the complicated synergistic effects of proposed CO_2 mitigation strategies on water demand and pollution emissions, and to design more effective policies and measures to ensure energy and water security in the future.

1. Introduction

Providing reliable and sustainable energy and water service faces multiple challenges, including increasing demand due to population growth and economic development, water resources degradation, fossil energy resource depletion as well as climate change (Liu et al., 2016; WWAP, 2014). To ensure energy and water security as well as the adaptation to climate change, the Chinese government has implemented a series of CO_2 mitigation, energy and water saving, and pollutant emission reductions policies and measures. Recently, the Nationally Determined Contributions (NDC) in the Paris Agreement was announced to reduce CO_2 emission intensity (CO_2 emissions per unit of GDP) by 60%–65% in 2030 on the base of 2005 level (UNFCCC, 2015). At the same time, the 13th *Five-Year Plan for economic and social development* (NPC, 2016) proposes that energy and water use efficiency (energy and water use per unit of GDP) should be improved by 30% and 18% in 2020, respectively, compared with 2015 level. In addition, two main water pollutant control targets are set to improve surface water quality, including a 10% reduction of industrial chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) discharge in 2020 compared with 2015 level. Water and energy systems are interdependent, and thus policies and measures designed to increase the efficiency in one system might significantly affect another (Hussey and Pittock, 2012; Li et al., 2017; Rothausen and Conway, 2011). To aid decision-makers to meet these goals efficiently, there is a need to integrate CO_2 mitigation strategies with water resources management. The integrated approach helps better understand the links between energy and water systems and their dynamic interactions with socio-economic

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development and CO_2 emissions.

The impacts of CO_2 mitigation strategies on long-term economic and energy use have been widely studied (Dai et al., 2011; Dong et al., 2015; Wang et al., 2015; Wu et al., 2016). In China, several studies found that the implement of China's NDC can reduce CO_2 emission and energy consumption, and have adverse effects on economic output and employment in energy- and carbon-intensive industries (Dai et al., 2011; Dong et al., 2015; Wang et al., 2015; Wu et al., 2016). Furthermore, its co-benefits on air pollutant reduction (Dong et al., 2015) and health effects (Wu et al., 2017; Xie et al., 2016) have gained much attention recently. Recently, some energy-water nexus studies have been carried out to analyze the impacts of CO_2 mitigation strategies on energy use and water consumption in the power generation sector (Arent et al., 2014; Cameron et al., 2014; Chandel et al., 2011; Huang et al., 2017; Talati et al., 2016). These studies investigated water saving and CO_2 emission reduction under different CO_2 mitigation strategies and indicate that these strategies may increase or decrease water consumption due to the wide range of water use intensity of low-carbon emissions technologies choices (Kyle et al., 2013; Liu et al., 2015; Talati et al., 2016). Also, there are increasingly integrated modeling tools considering the broader nexus of water, energy, and food system for CO_2 mitigation and climate adaptation purposes (Ermolieva et al., 2015; Howells et al., 2013; Kraucunas et al., 2015; Martinez-Hernandez et al., 2017). CO_2 mitigation strategies involving a carbon price can also promote the adjustment of industry structure to a low-carbon, high energy efficient one (Dong et al., 2015; Dong and Liang, 2014; Xing et al., 2011), which have extensive impacts on the water consumption and pollutant discharge in the economic system (Cooper and Sehlke, 2012). However, these cross-sector feedbacks have not been fully considered in current water-energy nexus studies. In addition, a whole economic-wide assessment of the impacts of CO_2 mitigation on water pollutant emission reduction is in lacking. Some studies have assessed energy conservation and pollutant reduction using a technology-based bottom-up model in China's pulp and paper (Wen et al., 2015) and steel sectors (Wang et al., 2017). There are few studies integrating energy use, CO_2 emissions, economic and population growth, water resource stress and water quality change. An integrated model capturing the feedbacks among socio-economic, energy, and water systems is needed to help policymakers identify the possible co-benefits across these systems and formulate more effective policies and measures.

Available energy models and water system models assess CO_2 mitigation strategies and water engineering measures independently. In energy system, Long-range Energy Alternatives Planning (LEAP) (Heaps, 2016) and The Integrated MARKAL-EFOM System (TIMES) (Loulou et al., 2005) have been used to predict long-term energy planning and CO_2 mitigation. Compared with these methods, Computable General Equilibrium (CGE) model has been widely used to simulate the full range of future economic system (e.g. industry output, domestic and international trade) and energy system (e.g. energy supply, consumption and trade) (Cheng et al., 2016; Dai et al., 2011, 2016, 2012; Dong et al., 2015; Xie et al., 2016). In water system, many integrated water management models such as Water Evaluation And Planning (WEAP) (Hollermann et al., 2010; Illich, 2006; Li et al., 2015; Yates et al., 2005), Elbe-DSS (de Kok et al., 2009; Hahn et al., 2009; Lautenbach et al., 2009), System Dynamics and Water Environmental Model (SyDWEM) (Qin et al., 2011, 2013) are developed to evaluate effects of series of socio-economic and water engineering measures on water environment management. These integrated water models have been coupled with currently available energy models (e.g., the integration of LEAP and WEAP) to support planning for both water and energy system (Howells et al., 2013). However, the socio-economic components (e.g., population and economic growth rate) in these studies are regarded as external scenarios and fixed, and thus the feedbacks between different socio-economic components and between energy and water system cannot be effectively captured (de Kok et al., 2009; Lautenbach et al., 2009; Qin et al., 2013). The SyDWEM (Qin et al., 2011) model developed in our previous studies provides a useful tool to better understand the interactions among socioeconomic, water infrastructure, and receiving water systems by treating the socio-economic dynamics as an internal sub-module. The SyDWEM model has been successfully applied to a rapidly urbanizing coastal region (Qin et al., 2011, 2013).

In this study, a CGE model was integrated with the upgraded version of SyDWEM (CGE-SyDWEM) to simulate energy and water systems simultaneously and support the decision-making regarding management of energy and water resources and carbon reduction policy. Using this integrated model, planners from water and energy sectors could examine the cross-sectoral feedbacks, especially the impacts of CO_2 mitigation strategies on water demand and pollutant discharges as well as water quality. In this study, water demand, or water withdrawal, is defined as the amount of water withdrawn from all water resources, including local groundwater and surface water resources, water transfer from other catchment, and reclaimed wastewater reuse. The Shenzhen River Estuary catchment located in a rapidly urbanizing coastal region of Southeast China (Fig. A.1) was chosen as the study area. With rapid economic and population growth, the Shenzhen River Estuary catchment is facing challenges to meet the increasing water and energy demand. This study aims (1) to examine the performance of the integrated CGE-SyDWEM in simulating the interactions among socioeconomic, energy, carbon and water environmental systems; (2) to evaluate the co-benefit of CO_2 mitigation strategies on water use saving and pollutant emission reduction; and (3) to assess if the current water engineering measures can satisfy water demand, water pollutant reduction, and water environmental targets.

2. Methodology

2.1. IMED|CGE model

The IMED|CGE (**I**ntegrated **M**odel of **E**nergy, **E**nvironment and **E**conomy for Sustainable **D**evelopment | **C**omputable **G**eneral **E**quilibrium) model applied in this study can be classified as a 25-sector (Table A.1), 1-region, recursive dynamic CGE model developed for Shenzhen City by the Laboratory of Energy & Environmental Economics and Policy (LEEEP) at Peking University. The 2007 input and output table and 2007 energy balance table for Shenzhen are used for the base year calibration. The major features of the model are similar to the one-region version (Dai et al., 2012), including a production block, government and household incomes and expenditures blocks, and a market block with domestic and international transactions. The activity output for each sector follows a nested constant elasticity of substitution (CES) production function. Inputs are categorized into material commodities, energy commodities, labor, capital and resources. More technical descriptions can be found in Appendix B or available at http://scholar.pku.edu.cn/hanchengdai/imedcge.

2.2. SyDWEM

SyDWEM was developed to describe the socio-economic, water infrastructure, and the change of receiving water system in the Shenzhen River catchment during 1990–2020 (Qin et al., 2011, 2013) (equations and parameters are accessed at the webpage of http://see.szpku.edu.cn/qhp_sydwem.aspx.) The model is upgraded to meet our requirements in this study in the following five aspects: (1) The simulation period was extended to the year 2025. The simulations results of labor productivity for each industry in 2025 have been compared with the corresponding data in Japan (JPC, 2016) and Hong Kong (Census and statistics department of Hong Kong, 2016) to guarantee the projection for each industry falling in a reasonable range; (2) Previous industrial structure was considered as a decision variable, and its effect on GRP and population growth was evaluated using scenario analysis. However, in the updated SyDWEM, the industrial structure is predicted by

CGE model and treated as an inner-module of the integrated model. (3) Nanshan District and associated sub-catchments in the Shenzhen Estuary are added. The estimated parameter values for GRP growth of Nanshan District are shown in Table A.2 (4) Two additional water quality parameters (i.e., BOD_5 and NH_3-N); are incorporated into the updated model; and (5) The river water quality model has been upgraded to a two-dimensional (2D) model from a one-dimensional model. The details of the input parameter values for the upgraded SyDWEM can be found in Table A.3. The main components and functions for each module are described as follows:

(1) *Population/GRP module*: Population is determined by the projection of birth, death and labor force migration. Labor force migration dominates the population growth in rapidly urbanizing areas and is interacted with economic growth. Furthermore, labor force and net investment are the two main drivers of future growth of GRP (Qin et al., 2011). The Population and GRP model are integrated by the labor force, in which GRP is calculated based on Cobb-Douglas production function. The future labor force demand is determined by the projected changes in labor productivity and industry structure. SyDWEM can simulate GRP and population growth at administrative and sub-catchment scale.

(2) *Water demand/pollutant generation module:* The domestic and industrial water demand and BOD_5 and NH_3-N generation are predicted in this module. Water demand and pollutant generation from all sectors are based on population growth, economic development, water use efficiency, pollutants loading per capita and per GRP, and the projected changes in the industrial structure under a different scenario.

(3) *Water supply module:* Water supply capacity is based on the calculation of local water groundwater and surface water resources, available reclaimed wastewater and water transfer from other catchment. Local groundwater and surface water resources are estimated from the groundwater resources development rate and rainwater collection ability in the reservoirs at the upstream of the Shenzhen River, respectively. Available reclaimed wastewater and water transfer from other catchment are based on the reclaimed wastewater reuse ratio and water transfer quota, respectively, which is in accordance with the water resources plan of the catchment. *(4) Sewer and WWTPs module*: The wastewater discharged into the receiving water includes wastewater linked to the sewer system and treated by WWTPs, untreated wastewater assumed to discharge into the nearby river, and part of the effluent of WWTPs which may be reused and back to the water supply module. For example, policymakers can adjust the reclaimed wastewater reuse ratio to provide more water for residential or industrial reuse. The efficiency of wastewater treatment infrastructure influences the amount of wastewater and pollutant discharged into the receiving water and the amount of wastewater reused in industries and domestic activities.

(5) *Receiving water module:* Environmental Fluid Dynamic Code (EFDC) (Hamrick, 2006) is employed to simulate hydrodynamics and water quality change in the Shenzhen River Estuary. Since the estuary is very shallow, unstratified, and well-mixed, a two-dimensional (2D) depth-averaged tidal flow model is developed. The model contains 2382 active grid cells, covering the entire Shenzhen River Estuary. The size of the girds varies with the distance from the river drainage point, i.e. comparative smaller cells are near the river mouth (around 100*100 m) and larger cells are in the mouth of the Bay (around 250*250 m). The open boundary located in the southwest of Deep Bay (Chiwan). Water level for the open boundary is obtained from the tide table of South China Sea. The upstream boundary discharge was obtained from the measurements by Hu (2007). The BOD_5 and NH_3-N are taken as representative variables of water quality. The EFDC model runs at a time step of 10 s with a cold start of 15 days to obtain initial conditions, and another 15 days for result analysis. Parameters required for the EFDC of Shenzhen River Estuary have been calibrated by in our previous study (Su et al., 2014). The upgraded SyDWEM was then validated using observed data from 2002 to 2009 for GRP, Population, and Water demand (Fig. A.2). Maximum relative error (M) and normalized standard error (E) are used to evaluate model performance. The M and E are calculated using Eq. (1) and Eq. (2). The M for GRP, population and water consumption in different districts/town ranges from 0.0% to 9.8%; and E ranges from 1.0% to 2.6%. The simulated wastewater and pollutants discharge by SyDWEM in 2004 were used for water quality model input. The model was further validated using the water quality data obtained in the water sampling monitoring during 17–18 and 25–26, Oct 2004. Eight temporary stations were established (Fig. A.1). Water level, BOD_5 and NH_3-N at the three stations, including S03 (at river drainage point), S05 (at inner Bay) and S06 (at outer Bay), are chosen to compare with measured data. The correlation coefficients for water level, BOD_5 and NH_3-N at the three stations (S03, S05, S06) range from 0.92 to 0.97, 0.67 to 0.84, and 0.65 to 0.73, respectively (Fig. A.3). The validation results indicate that the updated SyDWEM model can simulate the relationship among GRP, population, water demand and wastewater treatment as well as spatial and temporal variation of hydrodynamics and water quality in the Shenzhen River estuary.

$$M = max\,(S_i - M_i)/M_i \tag{1}$$

$$E = \frac{\sqrt{1/n(n-1)\sum_{i=1}^{n}(S_i - M_i)^2}}{\frac{1}{n}\sum_{i=1}^{n}M_i} \tag{2}$$

where, S_i is the i th simulated value; M_i is the corresponding measured value and n is the number of measurements.

2.3. Integrated CGE-SyDWEM model

Fig. 1 illustrates the conceptual integration of CGE model and SyDWEM model. The energy-water system in the rapidly urbanizing catchment is a complex system, including socio-economic, energy, water infrastructure, and receiving water systems. CGE model is used to simulate the city-level socio-economic and energy system changes under CO_2 mitigation strategies. SyDWEM is used to simulate the sub-catchment level of socio-economic, water infrastructure, and receiving water systems. The two models are integrated through the socio-economic system. For example, the CGE model predicts city-level industrial output change under CO_2 mitigation strategies and then the SyDWEM model translates these changes into the sub-catchment level. Both models considered 25 sectors and SyDWEM further classifies them into five main sectors (Table A.1); primary industry (e.g. agriculture), three kinds of secondary industry (Labor-intensive industry e.g. textiles and paper products; technology-intensive industry e.g. electronic equipment and machinery; capital-intensive industry e.g. new material and energy industry) and tertiary industry (e.g. services industry). In order to unify the database of the two models, the relative change of industrial structure was used to integrate the two models. Also, the two models share the same inputs such as labor and capital. The interactions and feedbacks among different systems include: (1) CO_2 mitigation strategies affect socio-economic system, e.g., economic outputs in different industrial sectors, and energy system, e.g., CO_2 emissions and energy use; (2) Economic outputs of different industrial sectors influence sub-catchment level GRP change and labor force demand; (3) The sub-catchment level socio-economic change affects water demand and wastewater generation from domestic and industrial activities; (4) The spatial distribution of wastewater is simulated by the sewer and WWTPs systems and linked with water quality model; (5) Wastewater can be further treated and reclaimed, and becomes an important source of water supply system; (6) Water supply system supports population and

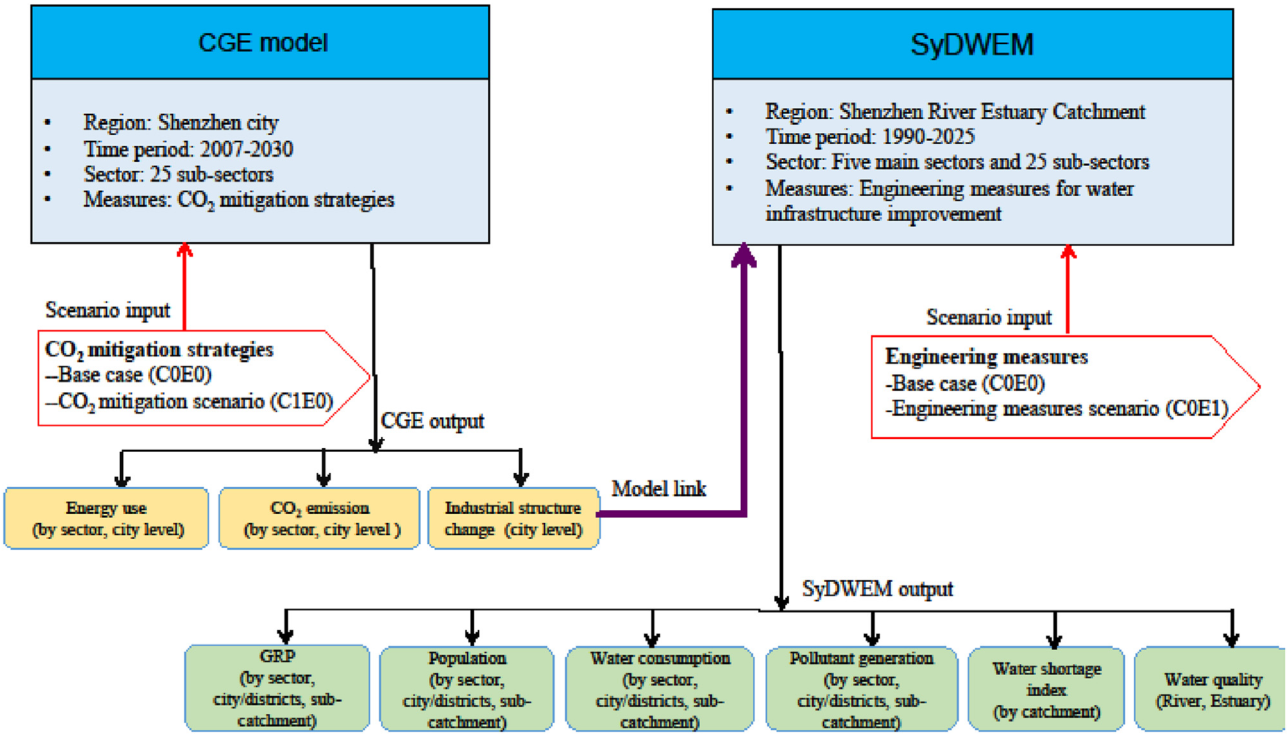

Fig. 1. The conceptual integration of computable general equilibrium (CGE), and System Dynamics and Water Environmental Model (SyDWEM).

economic development; (7) The implementation of water engineering measures (e.g., wastewater treatment, reuse, and water supply) might lead to additional energy use and CO_2 emissions. If the change is small compared with the overall energy use and CO_2 emissions in the study area, this feedback might be negligible. Using the integrated model, energy planner can evaluate the proposed CO_2 mitigation strategies on water demand and pollution emissions. Water planner can better understand the rapid socio-economic development and provide effective support for population and economic growth. Also, the impacts of water engineering measures on energy use and CO_2 emissions can be evaluated by energy planner.

Understanding the spatial and temporal scale differences is important in the model coupling. For spatial scales, socio-economic and energy system are developed at the administrative district level; sewer and WWTPs systems are based on their service area; water supply and receiving water system are considered for the catchment level. To address these scaling issues, the spatial data including GRP, population, water demand, and pollutant generation, are assumed uniformly distributed in the built-up area of the catchment. Accordingly, the spatial data can be rescaled into district/sub-catchment level based on the percentage of the built-up area. For temporal scales, socio-economic and energy system are projected at an annual step; water demand and supply, sewer and WWTPs system are simulated at daily step; receiving water model is set to seconds to capture the dynamic variations of flow and water quality in the estuary area. The annual and daily data could be downscaled to the smallest units of seconds for model coupling.

2.4. Scenario setting

Four scenarios, including C0E0, C1E0, C0E1 and C1E1, were set up to address the research questions (Table 1). C0E0 is a reference scenario that simulates the socio-economic, energy and water system change without the implementation of CO_2 mitigation strategies or engineering measures. The future economic and population growth of Shenzhen in CGE model was based on the results from the base case scenario of the previous version of SyDWEM (Qin et al., 2011) and are provided in Table A.2. The capacity and technology of water infrastructure system in 2009 will persist between 2010 and 2025. C1E0 scenario evaluates the effects of CO_2 mitigation strategies. This scenario differs from the reference scenario only in that it includes a constraint on CO_2 emissions. A carbon cap is set so that the CO_2 emission intensity of Shenzhen will be reduced by 45% in 2020 and 65% in 2030 compared with the 2007 level, which is consistent with China's newly announced NDC.

C0E1 scenario evaluates the effects of engineering measures on future stresses on water resources and water quality changes in the catchment. The development of the socio-economic system in the future is the same as C0E0, and there is no CO_2 emission intensity constraint. Table 2 lists water engineering measures assessed in this study, including three categories based on their intended goals; (1) Improving water use efficiency (M1, M2); (2) Increasing water supply capacity (M3, M4); (3) Increasing the efficiency of wastewater infrastructure system (M5, M6). These measures are based on the water infrastructures planning of Shenzhen (SZUPLRB, 2003), and the sensitivity analysis and possible range of each measure have been analyzed in our earlier study (Qin et al., 2013), and summarized in Table 2.

3. Results

3.1. Energy consumption and CO_2 emissions

The total primary energy consumption under C0E0 will increase to 0.46 EJ in 2025, which is more than twice of the 2007 level (Fig. 2a). However, under the C1E0 scenario, the primary energy consumption shows a decreasing trend during 2015–2020, and then slight increases to 0.17 EJ in 2025, which is only 41% of that in the reference scenario. The energy intensity in terms of GRP improves at an average annual increase rate of 9.1% in the C1E0 scenario, fulfilling the 30% regional improvement target during 2015–2020.

The trend of the CO_2 emissions under C0E0 is in alignment with the primary energy consumption, showing a significant growth from 69.7 million ton (Mt) in 2007 to 317.9 Mt in 2025 (Fig. 2b), equivalent to an annual growth rate of 9.5% and 8.0% for the periods of 2015–2020 and 2020–2025, respectively. However, with the CO_2 emissions intensity constraints, the CO_2 emissions show a decreasing trend after 2015.

Table 1
Configurations for the four scenarios.

Scenario	GDP growth rate in CGE model	Population growth rate In CGE model	Emission constraints	Engineering measures
C0E0	9.1% over 2007–2020; 7.9% over 2007–2030	0.57% over 2007–2020; 0.42% over 2007–2030	No emission constraints	No engineering measures upgraded in 2025
C1E0	Same as C0E0	Same as C0E0	Emission intensity reduced by 40% in 2020 and 65% in 2030	Same as C0E0
C0E1	Same as C0E0	Same as C0E0	Same as C0E0	Engineering measures upgraded
C1E1	Same as C0E0	Same as C0E0	Same as C1E0	Same as C0E1

Table 2
Summary of water engineering measures.

Measures/decision parameters	The possible % increase relative to Base case
M1: Industrial water recycling technology upgrade	10%
M2: Decreasing pipeline leakage	5%
M3: Increasing water transfer	20%
M4: Increase reclaimed wastewater reuse	10%
M5: Improving the volumetric wastewater treatment rate	Increase to 90%
M6: Pollutants removal rate of WWTPs	Increase to 80% (NH_3-N) and 90% (BOD_5)

Carbon mitigation strategies have the potential to reduce CO_2 emissions by 172.9 Mt (46%) in 2025, compared with reference scenario. The carbon intensity (CO_2 emissions per GRP) in 2025 will decrease to 58% of the 2007 level, fulfilling the regional NDC target.

CO_2 mitigation strategies could substantially reduce energy use and CO_2 emissions, and improve energy use efficiency and carbon intensity. The main reason is that with the CO_2 emission intensity constraint under C1E0 scenario, carbon emission allowance becomes a scarce resource and has a carbon shadow price that could be regarded as the marginal mitigation cost of carbon reduction. The carbon price is an equilibrium price that could balance the supply and demand of the carbon emission allowance. Supply of carbon emissions is implied by the carbon intensity target and future GDP, whereas the demand of the carbon emissions is represented by the emissions required by different industrial sectors and households, which is affected by the industrial output and income level. The carbon price will increase the production prices of all sectors depending on its carbon intensity. On the demand side, consumers will adjust their activities to lower the demand for energy- and carbon-intensive products. As a result, the output of some typical energy- and carbon-intensive industries such as textile, food production, chemicals and non-metal will be greatly reduced because of the comparatively high carbon emissions, leading to the change of industrial structure (Table A.5). For example, compared with C0E0, the proportion of labor-intensive industries and technology-intensive decreases by 4% and 2%, respectively, and the proportion of capital-intensive industries increases by 5%.

3.2. GRP and labor force

CO_2 mitigation strategies will slightly decrease GRP and labor force migration in the catchment due to the change of industrial structure. Because capital-intensive industries have higher labor productivity than the other two industries, e.g., labor productivity of capital-intensive industries is 17 and 5 times of technology-intensive and capital-intensive industries (Table A.5-A.6), and thus the total labor productivity improves by 3.6% in 2025 with the increased proportion of capital-intensive industries (Table A.5-A.6). Less labor force is required to maintain the same GRP growth rate. Under C0E0 it is projected that GRP will increase from 229.6 billion Yuan in 2010 to 818.0 billion Yuan in 2025 (Fig. 2c). GRP grows very quickly at the early stage of urbanization (1990–2000) with an annual growth rate of 19%, but its growth rate will slow down after 2007 to a nearly constant rate around of 8.0% later on. The relatively slow growth rate of GRP after 2007 is mainly attributed to the decreasing return of capital in all administrative areas (PGSZM, 2008). The GRP variation curve under C1E0 scenario nearly overlaps that under C0E0, and the GRP losses compared with C0E0 at 2025 is 0.7%.

Labor force migration is the main determinant of population growth of Shenzhen and the migration population accounts for nearly 70% of the total population in 2016. The projected labor force demand under

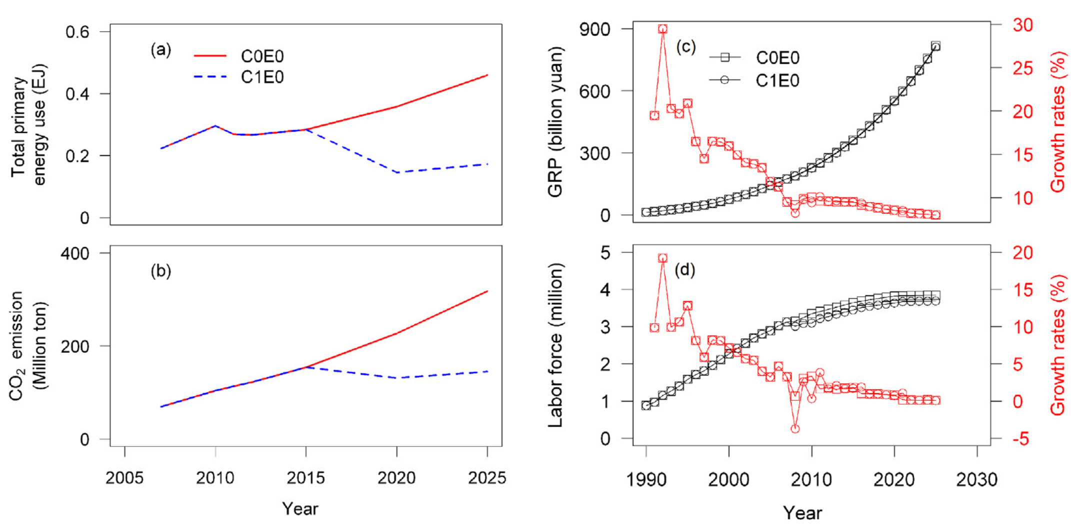

Fig. 2. Annual variation of (a) total primary energy consumption, (b) CO_2 emission, (c) GRP (with its growth rates), and (d) Labor force (with its growth rates) in Shenzhen under the references scenario (C0E0) and CO_2 mitigation scenario (C1E0).

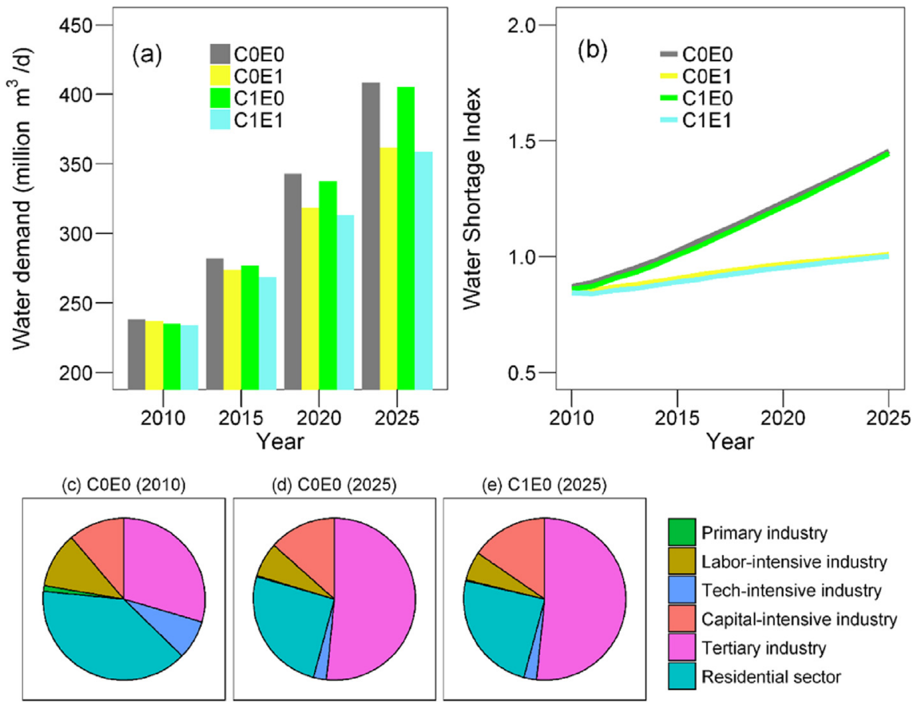

Fig. 3. Annual variations of (a) Total Water demand, (b) WSI and Sectoral water demand under different scenarios including (c) Current situation (2010) (d) C0E0 (2025) and (e) C1E0 (2025).

C0E0 increases from 3.12 million in 2007 to 3.85 million in 2025 with an average annual growth rate of 1.2% (Fig. 2d). This average annual growth rate is much smaller than that in the early stage of urbanization (nearly 10% during 1990–2000), due to the slower economic growth rate and improved labor productivity. Under C1E0, the projected labor force demand grows at a lower annual average growth rate of 0.9% (Fig. 2d). Compared with C0E0, the projected labor force demand decreases by 0.16 million. Constant birth rate and death rates are assumed during 2010–2025, and the projected population decreases by 0.19 million compared with C0E0.

3.3. Stress on water resources

Water demand for Shenzhen River Estuary under C0E0 will grow continuously between 2010 and 2025, increasing from 2.38 to 4.08 million m^3/d (Fig. 3a). However, there will be a slight increase in the potential water supply due to the limited increase in the reclaimed wastewater reuse for residential and economic activities. Here we introduce water shortage index (WSI), defined as the ratio of water demand to potential water supply, to determine the degree of local water stress (Qin et al., 2013), with values greater than one indicating the condition of severe water limitation. Given that the growth of water demand is much greater than the potential water supply, WSI increases quickly to be greater than one after 2015 and reaches as high as 1.46 in 2025 (Fig. 3b), implying that the study area will suffer severe water deficit in the near future.

By implementing water engineering measures (C0E1), the total water demand will be reduced by 8.1% and WSI will decrease by 30.7% in 2025 compared with C0E0 (Fig. 3a and b). Since the WSI value under C0E1 will be close to one when approaching the year of 2025 (Fig. 3b), the water demand and water supply will be nearly in balance even if we employ engineering measures alone. With CO_2 mitigation strategies (C1E0), the total water demand in 2025 is expected to decrease by 0.8% relative to C0E0, including a $4.2 \times 10^4\ m^3/d$ reduction (4.1%) in the residential sector and a $4.7 \times 10^4\ m^3/d$ reduction (16.8%) in labor-intensive industry. However, water demand from capital-intensive industry will increase by 13.9%, and its proportions in sectoral water demand increase from 11% in 2010 to 13% (C0E0) and 15% (C1E0) in 2025, respectively (Fig. 3c, d and e). With the combination effects of engineering measures and CO_2 mitigation strategies, the total water demand in 2025 will be reduced by 12.2% relative to C0E0, and it will be balanced by the water supply.

3.4. Water quality change

Current water infrastructure system cannot provide sufficient service to collect and treat all wastewater. Fig. 4 shows that under the reference scenario total BOD_5 and NH_3-N generations from residential and industrial sectors increase by 38.5% and 27.2% from 2010 to 2025. As a result, the projected BOD_5 and NH_3-N discharges into the river grow greatly from 2010 to 2025 under E0C0, with a total increase of 37.9% and 27.5% in 2025, respectively. CO_2 mitigation strategies (C1E0) have co-benefit on pollutant generation reduction (Fig. 4c, d), i.e. both BOD_5 and NH_3-N generations in 2025 will decrease by 4.2% and 4.4% compared with C0E0, including a 6.8 t/d (4.1%) and 2.9 t/d (4.1%) decrease in residential sector and a 3.4 t/d (6.8%) and 0.5 t/d (4.7%) decrease in secondary industry, respectively. Water engineering measures can further reduce pollutant discharges. Specifically, the projected BOD_5 and NH_3-N discharges under C0E1 scenario are reduced by 50.1% and 53.5% in 2025 compared with C0E0, respectively. The combined effects of CO_2 mitigation strategies and engineering measures on pollutant discharge evaluated via C1E1 scenario show that the total BOD_5 and NH_3-N discharges will decrease to 34.2 t/d and 10.9 t/d in 2025, respectively, corresponding to reduction rates of 29.2% and 39.0% on the basis of 2010 level.

Figs. 5 and 6 show the temporal and spatial water quality variation in the Shenzhen River Estuary under different scenarios. Water quality varies greatly at each station due to the combined effects of the tide and wastewater discharge. At station S03 and S05, NH_3-N concentration shows a slightly decreasing trend under C0E0, however, water quality continues to worsen at all other stations from 2010 to 2025, with the average concentration ranges of BOD_5 and NH_3-N in 2025 being 1.1–32.3 mg/L and 1.0–13.1 mg/L, respectively.

Under C1E0, water quality is slightly improved at all the four

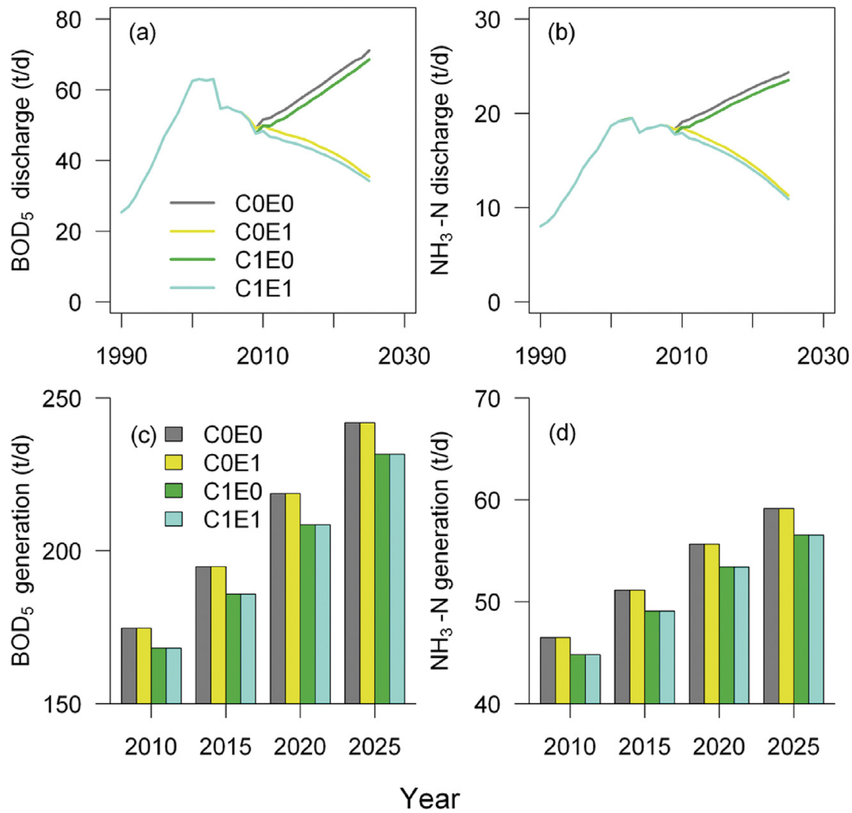

Fig. 4. Annual variations of BOD_5 loading/discharge (a and c) and NH_3-N loading/discharge (b and d) from 2010 to 2025 under different scenarios.

stations relative to C0E0, i.e., the BOD_5 and NH_3-N concentrations at S01, S03, S05 and S06 decrease by 0.7–2.7% and 1.3–5.2%, respectively. Without considering flood or ebb tide, the maximum concentrations of BOD_5 and NH_3-N occur at S01, where most of the untreated wastewater in the study area is discharged into the river. With engineering measures (C0E1), the projected BOD_5 and NH_3-N discharges reduce by 29.0% and 38.8% in 2025 compared with 2010 (Fig. 5c and d). Thus water quality will be substantially improved between 2010 and 2025. With integrated measures, the average BOD_5 and NH_3-N concentrations at S01 (where the water quality was impaired the worst) will decrease to 13.4 mg/L and 6.0 mg/L in 2025, only 45% and 46% of the 2010 level, respectively. As shown in Fig. 6, except some cross-sections in the middle reach of the river, water quality in Shenzhen River Estuary will satisfy the water quality level suggested by Hu (2007) and Su et al. (2014) to eliminate the malodorous-black phenomenon in the river, with average BOD_5 concentration lower than 10 mg/L and NH_3-N concentration lower than 6 mg/L.

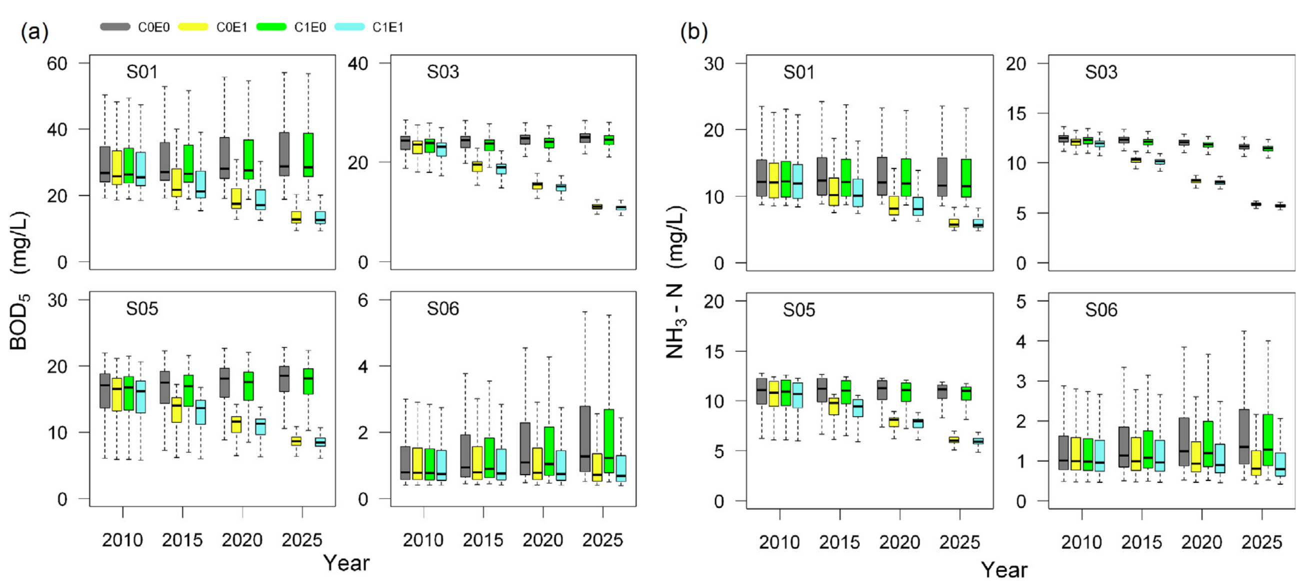

Fig. 5. Variations of (a) BOD_5 concentration and (b) NH_3-N concentration under different scenarios from 2010 to 2025 at four stations: (a) S01-Buji; (b) S03-Hekou; (c) S05-Tsim Bei Tsui; and (d) S06-Dongjiaotou (n = 337).

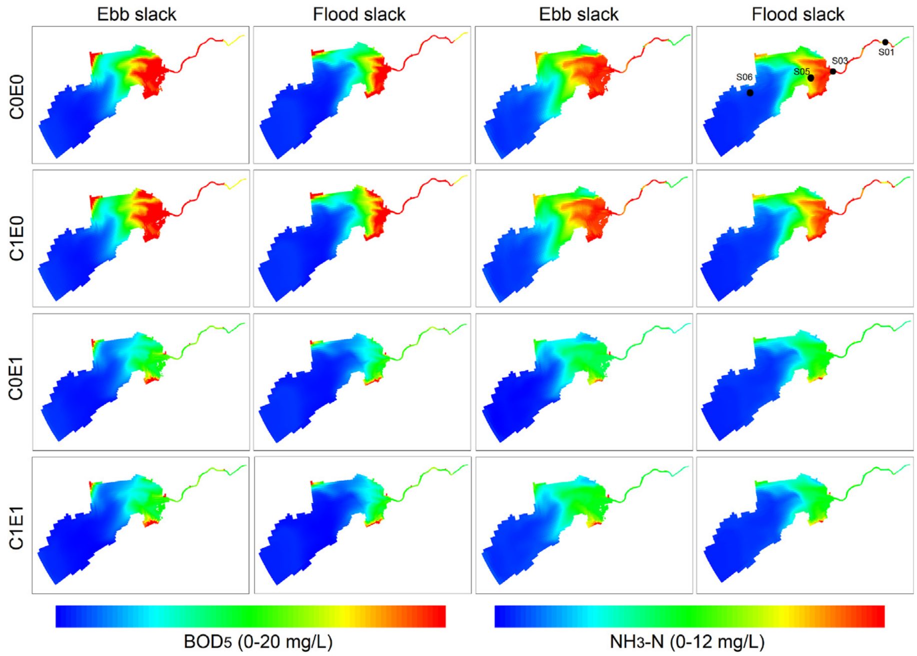

Fig. 6. Spatial distribution of BOD_5 and NH_3-N concentration during ebb slack and flood slack under different scenarios at 2025.

4. Discussion

4.1. Effects of CO_2 mitigation strategies on water use

The co-benefits of carbon mitigation strategies on water demand and pollutant discharge can be captured using the integrated model through the bridge of industrial structure change. For instance, by comparing C0E0 and C1E0 scenarios, the effects of CO_2 mitigation strategies on water saving could be evaluated. Compared with C0E0, economic growth in C1E0 decreases slightly since carbon emissions are not free of charge anymore. However, it could promote industrial structure adjustment leading to a decreasing proportion of energy- and carbon-intensive industry in the economic system. Since many of those industries are water intensive, such industrial adjustment has co-benefits on the water system. First, it significantly reduces water demand and pollutant discharge from the domestic sector. The reduction of the labor-intensive industry is beneficial to the acceleration of total labor productivity since its productivity is comparatively lower than other industries. Hence, the projected population growth under C1E0 scenario decreases by 4.1% compared with C0E0. Residential sector represents the most significant portion of water demand and pollutant discharge, which accounts for 39% (Fig. 3d), 79% (BOD_5), and 91% (NH_3-N) in 2010 under C0E0. The effects of CO_2 mitigation strategies on residential water demand and pollutant discharge reduction are significant to satisfy future water demand and local water environment standard. Second, it has co-benefits on reduction in secondary industry water demand and pollutant generation from labor-intensive and technology-intensive industries. Compared with technology- and capital-intensive industries, the labor-intensive industry has lower water use efficiency and higher pollutant discharge intensity. For example, the projected water use efficiency of the labor-intensive industry is 27% and 96% of technology-intensive and capital-intensive industries in 2025 (Table A.6), respectively. Also, the BOD_5 load and NH_3-N load per GRP of the labor-intensive industry are the highest in the three types of industries, e.g., its BOD_5 load and NH_3-N load per GRP is 4 times and 6 times of that of capital-intensive industries, respectively (Table A.7). Therefore, industrial upgrade away from labor-intensive to capital-intensive industries could help to save water and reduce water pollutants discharge. However, it should be noted that water demand from some capital-intensive industries, e.g., electricity production and supply, are expected to increase by 14% compared with C0E0 in 2025, which implies that more attention should be paid to water-saving technologies in these industries.

4.2. Effects of engineering measures

Water engineering measures can greatly alleviate water resource stress and improve water quality. The effects of engineering strategies are evaluated by the comparison of C0E0 and C0E1 scenarios. Current water infrastructure system cannot secure future adequacy of water resources and protect water environment based on the simulations in the reference scenario. From the water demand side, engineering measures can improve water use efficiency (about 16% compared with C0E0, Table A.5), by upgrading industrial water recycling technology and decreasing pipeline leakage. From the water supply side, engineering measures can increase the potential water supply by increasing water transfer quota and wastewater reuse. The water demand and water supply will be nearly in balance even if we employ engineering measures alone. However, this balance is very uncertain after 2025, because it is strongly dependent on the available quota of water transferred from other catchments, the increase of reclaimed wastewater reuse and the improvement of water use efficiency (Qin et al., 2013).

Furthermore, engineering measures can greatly reduce pollutants discharge and improve water quality by building new Wastewater Treatment Plants (WWTPs) and improving wastewater treatment capacity and efficiency of the current WWTPs. According to Shenzhen municipal wastewater system planning, three new WWTPs will be built (Fig. A.1) and equipped with tertiary treatment technology with 80% and 90% of NH_3-N and BOD_5 removal rates, respectively (PGSZM, 2008; Qin et al., 2014). Engineering measures are more efficient in reducing NH_3-N load than BOD_5 load, which is attributed to the relatively lower removal efficiencies for nutrients in existing WWTPs. For example, the average NH_3-N and BOD_5 removal rates of current WWTPs are 60% and 80%, respectively (PGSZM, 2008; Qin et al., 2014). NH_3-N loads reduction still has high potential considering the increasing need of using reclaimed wastewater as a potential water resource. However, engineering measures alone cannot meet the water quality improvement target of the study area.

4.3. Policy implications

The aggregated effects of both CO_2 mitigation strategies and engineering measures are evaluated by C1E1 scenario. The results show that a low-carbon, high-efficiency water and energy use economy and better water environment is potentially achievable. The CGE-SyDWEM integrated model can capture the linkage among socioeconomic, energy use, CO_2 emissions, water resource supply and depletion, as well as changes in the water system and is proved to be capable in analyzing the long-term scenario of rapid urbanization process. The integrated systems presented in this study can be used to aid energy planner to understand the effects proposed CO_2 mitigation strategies on energy use efficiency and its co-benefits on water use saving and pollution emission reduction. It can also aid water planner to analyze if current water engineering measures can support future water security under proposed CO_2 mitigation strategies and socio-economic development. Based on this integrated model, decision makers across different sectors can consult with each other in order to design more effective policies and measures to achieve national targets. It also implies that labor-intensive industries should pay more attention to cleaner technologies to reduce energy and water demand as well as pollutant discharge. To promote the use of cleaner technologies, economic incentives such as water tariff adjustment, emissions trading are encouraged (Qin et al., 2014; Su et al., 2009). Local government should also promote the water-saving appliances in public and household utilities to reduce residential water demand and seawater cooling in the electricity production and supply industry.

4.4. Sensitivity analysis

Uncertainties associated with all integrated models include (1) uncertainty in the assumptions of the socio-economic system in the CGE model; (2) uncertainty in the estimation of future water demand and pollutant discharge, which is associated with both parameters calibration in the SyDWEM model and the engineering measures settings; and (3) uncertainty in the performance of water quality model. We analyzed the first uncertainty by adding two additional GRP growth rates scenarios into the CGE model, i.e., a higher (10.4%) and a lower annual growth rate (7.7%), and the resulted industrial structure changes and investment changes are fed into the SyDWEM model leading to the changes in energy use, GRP loss, labor force, water demand, and water quality change (Table 3). As shown in Table 3, energy use, labor force migration and WSI are more sensitive to GRP changes than water quality change and GRP losses. For the secondary uncertainty, the calibration of labor productivity, water use efficiency, and pollutant loading in each industry has been analyzed in our earlier study (Qin et al., 2011). The predicted GRP, population, and water demand in different districts/towns have been validated with census data. Also, the sensitivity of each engineering measure on water demand and water quality change has been assessed (Qin et al., 2013). The major findings from our previous simulations are as follows. First, increasing water transfer (M3) can significantly alleviate water shortage but has no effects on water quality, e.g., with 0–20% increase of M3, water shortage index decreases by 0–15%. Second, measures aimed at increasing the efficiency of wastewater infrastructure system (M5 and M6) can greatly improve water quality in the river but have no impacts on water shortage alleviation, e.g., with 0–10% increase of M5 and M6, water quality (e.g., Chemical Oxygen Demand, COD) at Station S01 decreases by 0–30% (M5) and 0–23% (M6), respectively. Third, some measures are sensitive to both water demand and water quality change, e.g., water use efficiency increase (M1 and M2) and reclaimed wastewater reuse (M4) can alleviate water shortages, but can also decrease water quality (Qin et al., 2013). For example, with water use efficiency and M4 increase by 0–20% and 0–10%, water shortage index decreases by 0–10% and 0–2%, and COD at Station S01 increases by 0–8% and 0–9%, respectively. Furthermore, we analyzed their aggregated effects by adding two additional engineering measures scenarios, i.e., En_high and En_low, with M1 and M3-M6 increase or decrease 5%, and M2 increase or decrease 2.5% at 2025 compared with C1E1, respectively (Table 3). Water quality changes are more sensitive to engineering measures than WSI, and BOD_5 concentration is more sensitive than NH_3-N. In terms of uncertainty of the water quality module, two sets of water quality data obtained in the water sampling monitoring were used for model calibration and validation. The detailed result was provided in section 2.2. The results show that the water quality model can well capture the spatial and temporal variation of hydrodynamics and water quality in the Shenzhen River estuary.

4.5. Limitations and future work

This study quantified the feedback of carbon mitigation on water system. However, feedbacks of water engineering measures on carbon emissions are not included in the current integrated model due to lack of data. In fact, water engineering measures can also have impacts on energy use and CO_2 emissions because energy is required during water abstraction, treatment, and distribution phases. For example, energy use for water supply, distribution, and treatment accounts for 1.7–2.7% of the total primary energy use globally. In countries with the wide use of groundwater pumping for irrigation and thermal desalination, this share can be 3.0–10% (Liu et al., 2016). The additional energy use and CO_2 emissions of water engineering measures are important in capturing the feedbacks of water-energy nexus systems. Another reason is that the energy use for water in the study area is relatively small. For example, the oil use, coal use, electricity needs of water supply system (excluding end-water-use energy) of Shenzhen accounts for only 0.01%, 0.03% and 0.28% of total use (CSBS, 2015). Ignoring this additional feedback from future water engineering measures, energy demand and CO_2 emission may be underestimated. In addition, how water policy could affect energy consumption and carbon control target is also relevant but beyond the scope of this study. The Chinese government has raised targets on total water consumption and water intensity in terms of GDP, which has co-benefits or trade-offs with carbon mitigation target and deserves further quantitative evaluation.

5. Conclusions

A CGE-based integrated model for energy, carbon, and water management in a rapidly urbanizing catchment was developed to simulate the dynamic interactions between the socio-economic, energy, water environment system. Our simulations prove that the integrated model

Table 3
Changes from values in C1E1 in 2025 under sensitivity analysis.

Scenarios	Energy use	GRP loss	Labor force	WSI	BOD_5 loads	NH_3-N loads	BOD_5[a]	NH_3-N[a]
S1.GRP_high	23.9%	5.1%	12.1%	12.1%	12.8%	12.5%	4.1%	5.6%
S2: GRP_low	−17.0%	−4.5%	12.7%	−11.5%	−11.0%	−11.0%	−3.2%	−4.8%
S3: EN_high	0	0	0	−11.7%	−47.2%	−36.1%	−44.6%	−29.4%
S4: EN_low	0	0	0	14.5%	46.7%	35.9%	40.4%	26.1%

Note:
[a] Represents average water quality at water quality station S01 in 2025.

was able to assess the effects of proposed CO_2 mitigation strategies and water-engineering measures on future energy use, carbon emission, economic and population growth, water resource stress and water quality change at a watershed level. The integrated model improves the understanding of how climate mitigation policy in the energy sector might affect the ability to meet water quantity and quality targets in the water sector. Our results show that CO_2 mitigation strategies can promote local industrial structure adjustment by decreasing the output of energy-and water-intensive industries. Its co-benefits on domestic and industrial water use and pollutant discharge reduction are important to satisfy local water demand and fulfill the water quality improvement target.

This integrated model facilitates the communications among different planners and policymakers and enables a better understanding of the carbon-energy-water nexus. Although the current study focuses on a rapidly urbanizing catchment in southeast China, the framework could be used in other urbanizing catchments, especially in developing countries with rapid population and economic change. The domain of analysis and the choice of sub-modules could have regional differences. For example, in regions with a higher proportion of agriculture industry, the sub-modules for irrigation water demand and non-point pollutants discharge estimation vary according to regional issues. We also recognized that the additional energy use and CO_2 emissions of water engineering measures are neglected in the current study. One of our future priorities is to add these feedbacks and their impacts on economic development into the integrated model. In addition, the emphasis of this paper is to capture the cross-sector interactions and feedbacks and to provide an integrated view of the impacts of carbon mitigation strategies on all industrial sectors in the economic system. Thus, the impacts of using different technologies on the carbon-energy-water interactions in a single sector are not simulated, which limits its application in single sector planning. This limitation could be improved in the future with the availability of detailed sector data, which is still a challenging in developing countries due to data limitations.

Author contributions

Q.S. and H.C.D designed the research and developed the integrated model; Q. S., H.C.D., Y.L., H.C., analyzed data; Q.S., H.C.D., R.K., wrote the paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.07.071.

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